A METEOROID "SUPER–VOLCANISM" ON THE EARTH AND MARS IN THE HADEAN EON. M.Lefort1 and M.Maurette2, 1Institut Charles Sadron, BP 84047, 67034 Strasbourg, France, 2CSNSM, Bat.108, 91405-Orsay, Campus, France. maurette@csnsm.in2p3.fr.

Introduction: Meteoroids with sizes ~100–200 μm represent the dominant mass fraction of the extraterrestrial material accreted by the Earth. Those that survive unmelting upon atmospheric entry can be recovered as micrometeorites in Antarctica ices and snows (AMMs). Their analysis show that ~99% of the meteoroids are related to the most volatile–rich meteorites, the hydrous carbonaceous chondrites, and dominantly to the CM chondrites. Upon atmospheric entry, each meteoroid produces a radar shooting star and a tiny "puff" of gases and smoke particles that feed a meteoroid "volcanism", rooted around the thermopause. The meteoroid origin of the Earth’s atmosphere was already discussed [1, 2, 3]. In this abstract, we first outline the computation of the total amount of any meteoroid species accreted by the young Earth and Mars, since the merging of their last planetary embryo, at time, t1. These computations are next exploited to decrypt the Hadean meteoroid sulfur cycle on both planets and its effects on their climates. In a companion abstract [4], we turn to Spirit and Opportunity to better constraint the origin of the thin contemporary Martian atmosphere.

A meteoroid accretion equation:
Earth: The self–erasing mega–impact by the last planetary embryo (about 10 lunar mass) did form the Moon at time, t1, which corresponds to the formation age of the oldest lunar highland rocks (~4.44 Ga). It also simultaneously closed the formation time interval of the Earth and blew off its intractable pre-lunar atmosphere. Next, during the first ~100–200 Ma of the post-lunar period, meteoroids generated a new atmosphere. Their mass input rate was exponentially decaying with time, accordingly to the dimensionless relative lunar cratering rates, K(t), conjectured by Hartmann and subsequently improved by Neukum [5]. Indeed, one could expect that both the lunar impactors and the parent bodies of meteoroids were dominantly extracted from the same reservoirs of bodies. If the impactor number mass flux is K(t) higher than today, the meteoroid mass flux will be multiplied by the same factor (cf. Ref. 6, p. 273). In particular, the total amount, M1, of a given meteoroid species, A, delivered to the Earth scales as:

\[ M_1 \sim [A \text{wt.} \%] \times 10^{-3} \times \Phi_E(t_1). \]

In this accretion formula, A( wt. %) and \( \Phi_E(t_1) \) are the wt. % concentration of a given species, A, measured in unmelted Antarctica micrometeorites, and the integrated mass flux of meteoroids since the formation of the Moon, at time, t1 = ~4.44 Ga, respectively. The major problem hiding in this simple formula is the value of \( \Phi_E(t_1) \), which was estimated with 3 totally independent methods [1, 2, 3]. The similarity (within a factor 2) of these 3 estimates validated using the "lunar" value, \( \Phi_E(t_1) \sim 5.6 \times 10^{11} \text{g}, \) duced from the integration of the K(t) curve.

Mars: The extrapolation to Mars required estimating the value of \( \Phi_{Mar}(t_1) \sim 10^{21} \text{g}, \) from \( \Phi_E(t_1) \), just considering: (i) the ratio of the gravitational focusing factors of the 2 planets with an updated meteoroid approach velocity, \( V_{a,m} \sim 20 \text{ km s}^{-1}, \) corresponding to that expected for cometary debris (AMMs are very similar to the Wild 2 dust particles returned by Star-dust); (ii) the variation of the meteoroid flux between ~1 and 1.5 AU, which approximately scales inversely to the heliocentric distance (see Ref. 7, Fig. 42, from Eberhard Grün); (iii) the timing of the first shot at \( t_1 \sim 4.44 \text{ Ga}, \) like on Earth (see Introduction in Ref. 4).

The meteoroid purity of the Earth’s atmosphere: The accuracy of the meteoroid predictions is best constrained on the Earth. It can be characterized by a mass "misfit-ratio" (reported in bold–italics) between the predicted and observed amounts of a given species, A, in a selection of species that widely differ in both their chemical properties and concentrations in AMMs, and such as : Ne (1.2), N2 (0.98), H2O (0.40), CO2 (1.55), S (1.24), Ir (1.06), Os (0.89) and Ru (1.03). The worst fit was observed for H2O. One of the major finding was the impressive fits observed for S, Ir, Os and Ru, when the predicted amounts are compared to the corresponding total amounts hosted in the constituent sulfides of upper mantle rocks [2]. Therefore, the total mass of sulfur in the upper mantle would well corresponds to that released as SO2 from meteorite sulfide (troilite) upon atmospheric entry. We likely hold the initial (meteoroid troilite) and final (FeS in the upper mantle) stages of the early meteoroid sulfur cycle on the Earth. We next try to identify its intermediate stages, and in Ref. 4, we question how the missing plate tectonics affected the sulfur cycle on Mars.

From H2SO4 vapor to droplets of acid–sulfate aerosols: Like in any classical basalt magma volcanic eruption, the oxidation of meteorite sulfide into SO2 can be attributed to a kind of in–situ oxidation, which is related to the oxygen fugacity of their assemblage of minerals that mostly depend on their anhydrous silicates and iron contents. About 30 years ago, Hofmann and Rosen [8] noted: "The formation mechanism of stratospheric H2SO4 vapor, which is postulated to be a precursor of stratospheric aerosols, is not known. It has been conjectured to be formed in the stratosphere from the reaction of water and SOx, the latter being derived from the oxidation of SO2". This concise statement is still valid, even though the formation and evolution of volcanic species in the early Earth atmosphere are now described with commercial softwares with up to 214 reactions (including about 40 S–rich species) in both chemistry and the complex microphysics of the condensation of H2SO4 vapor into dirty acid droplets [9]. We skipped this intimidating reaction network, just relying on experimental studies of these aerosols for 3 modern eruptions that ejected material into the stratosphere (Agung, El-Chichon and Pinatubo). Both instruments on space probes and analyses of the acid aerosol fallouts in polar snows, led to 3 important observations: (i) sulfate aerosols are formed in ~2–3 weeks after injection of SO2 in the stratosphere; (ii) their lifetimes against gravitational settling on Earth is ~4–5 years; (iii) they reflect sunlight back to space and cool the Earth.

Heavy weathering of early sialic crusts: The enormous mass input rates of meteorite SO2, H2O and CO2 were about similar, during the first ~100 Ma of the post-lunar meteoroid. They reached values of ~4,000 Mt yr−1 and ~800...
Mt yr⁻¹ for the Earth and Mars, respectively. About 2/3 of the meteoroid water, as well as meteoroid "smoke" particles, were likely involved in the formation of sulfate aerosols. They did quickly rain on the Earth and Mars as dirty liquid droplets and/or hail stones, while being constantly generated by the exponentially decaying input rates of SO₂ and H₂O, during the first 100–200 Ma of the post-lunar period.

The next effect of this acrid rain (pH ~0), on both planets, was a very heavy acidic weathering of a thin silicic crust, which was a prerequisite to the formation of old (≥ 4.3 Ga) Australian zircons [10]. It also prevented the scavenging of CO₂ in carbonates. However, the dates of these initial loads of aerosols subsequently diverged on the two planets, as plate tectonics was "missing" on Mars. On the Earth, a fast "platelet" tectonics [11] was likely driving a massive attack of the oceanic crust by strongly acidic water. This generated a world wide hydrothermal system, where sulfates were likely transformed into iron sulfides and subducted to the upper mantle (see 3rd section). What were the implications of these earlier similar stages of the meteoroid sulfur cycle on both planets?

A benign Hadean climate back to 4.3 Ga ago: Climatic models attempted to fabricate the mild climatic conditions required for the birth of life on Earth, around 4 Ga ago. These mild conditions have now been established from the oxygen isotopic composition, the lithium concentration and the U–Pb age of a few old Australian zircons with ages ~4.3 Ga [10]. These models rely on the reduced luminosity of the "faint" early Sun (by a factor ~30%), which would have frozen the oceans of both Mars and the Earth. With adjustable parameters any model can rightly counterbalance this cooling with greenhouse gases (CO₂, O₂, and CH₄) outgassed from the Earth. They ignored both the early roles of water and the Moon forming impact, which blew off the pre-lunar greenhouse gases at a time when the young Earth was almost fully degassed. This left a niche for a meteoroid "super–volcanism", which probably dominated the climatic effects of the faint residual volcanism expected from the strongly degassed upper mantle.

The problem worsened in 2002 with the high S contents (~5%) measured in AMMs [12]. The accretion equation predicts the formation of huge input rates of sulfate aerosol droplets at high elevation, on the Earth, Mars and Venus. They reflected sunlight back to space and cooled the Earth, thus enhancing the cooling effect of the faint early Sun! This effect is well established for the most explosive volcanic eruptions that inject material in the stratosphere, such as Pinatubo (1991), Tambora (1815) and the Toba super–eruption (74,000 yr ago), which outgassed ~1000–5000 Mt of SO₂ in about 2 weeks. It triggered a "volcanic winter" that likely decreased the global temperature by ~4–5°C for a few years [13]. This Toba aerosol burden is rather similar to the corresponding expected meteoroid value (~4000 Mt yr⁻¹) on Earth, which was effective for ~100 Ma.

How did the Earth and Mars manage to avoid a ~200 Ma long volcanic winter that runs against the mild climate en-crypted in the old Australian zircons, which requires the existence of liquid water and continents back to ~4.3 Ga ago? Indeed, the Toba aerosols alone would have attenuated solar light by ~10³'s! Some processes had to heat up the kind of giant cocoon of "smoke" particles, aerosols and gases generated by the meteoroid volcanism. They possibly included: (i) the frictional heating of air molecules against the leading edge of meteoroids upon atmospheric entry that released about 130–6400 erg cm⁻² s⁻¹ (see Ref. 7, p. 270); (ii) the latent heat of condensation of hot water vapor (released by shooting stars) into ice (≥ 2800 joules g⁻¹); (iii) the formation of strongly acidic oceans that prevented the scavenging of CO₂ into carbonate. The resulting increase of the CO₂ partial pressure could trigger a strong greenhouse effect on both the Earth and Mars.

But on the Earth this effect was limited, as the total burden of meteoroid CO₂ was found to be fully stored as carbonates in the crust. This is likely related to plate tectonics that shielded sulfur at great depths in the Earth's upper mantle (see 3rd section). The pH of ocean water could increase up to the critical value (~6) where CO₂ starts precipitating as carbonates. Simultaneously, the meteoroid delivery of SO₂ and CO₂ was sharply decaying by a factor ~100x during the first 200 Ma of the post-lunar period. However, on Mars, the missing plate tectonics could just allow a massive impregna-tion of the porous megaregolith with low pH waters [4], which perennially prevented the scavenging of CO₂ into carbonates. Therefore, CO₂ accumulated in the Martian "air", ready to be blown off at t₂, like Ne and N₂. Then, a frozen and red planet was born.

Summary: The complementary works described in our two companion abstracts involve a classical scenario of planetary evolution, which is rooted in the pioneering work of George Wetherill in the 1970's. The first "short" blew off, at about the same time, the intractable early atmosphere of Earth and Mars. Both planets were then immersed in the debris disk of the Sun, where the dominant debris were hy-drous carbonaceous meteoroids similar to contemporary AMMs. Early Earth's processes had to be finely tuned in time, as to deliver the right amounts of such vastly different species as Ne, H₂O and Ir (e.g., the concentration of Ne is about 10⁸ times smaller than that of H₂O). They had also to fully recycle meteoroid sulfur into the Earth's upper mantle. In our companion abstract [4], we further extend the Martian part of this investigation, with the help of Spirit and Opportunity, as to get clues about the effects of missing plate tectonics on the early atmosphere of the terrestrial planets.

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